T.1: Implementation of transverse multi-bunch feedback system in Indus-2

Surendra Yadav and T. A. Puntambekar
Beam Diagnostics & Coolant Systems Division
Email: syadav@rrcat.gov.in

The design and implementation of transverse multi-bunch feedback system for Indus-2 is a collaborative work accomplished by the joint effort of colleagues from Beam Diagnostics & Coolant Systems Division, Accelerator Physics Section, Accelerator Control Systems Division, RF Systems Division, Ultra High Vacuum Technology Section and working group for multi-bunch feedback system for Indus-2.

Abstract

Indus-2 is an electron synchrotron radiation source at Raja Ramanna Centre for Advanced Technology, Indore, which is operated at beam current up to 200 mA and beam energy 2.5 GeV. In Indus-2 storage ring, electron beam circulates in the form of bunches which interact with each other through electromagnetic field trapped in the surrounding metallic structure of vacuum chamber. This phenomenon consequently results in the growth of electron beam instabilities. These instabilities, also referred to as the coupled bunch instabilities, are a matter of concern in Indus-2 at beam current approximately above 150 mA. The electron bunches under these instabilities coherently oscillate with different relative phase differences. The phase difference between oscillation of consecutive bunches is expressed by coupled bunch mode (CBM) numbers. The CBM in transverse plane is known as transverse coupled bunch modes (TCBM). Significant growth of transverse beam instabilities was observed during high beam current operation using TCBM measurement system deployed in Indus-2. The effects of these instabilities are saturation of beam current during beam injection, partial beam loss etc. These instabilities are cured by deploying transverse multi-bunch feedback (TMBF) system in Indus-2 and beam current of 200 mA at 2.5 GeV beam energy has been achieved with good beam injection rate. Scheme of transverse coupled bunch instabilities measurement and TMBF system of Indus-2 are presented in this article. Various improvements in the performance of Indus-2 due to deployment of TMBF system are also exemplified in the article.

1. Introduction

The global scenario in the field of electron synchrotron radiation source has been to operate the accelerator at high electron beam current with small beam emittance to achieve high flux and high brightness of synchrotron radiation [1]. As charged particles travel in accelerators, they interact with the surrounding metallic structures of vacuum chamber and generate electromagnetic fields. These fields are referred to as wakefields. The wakefields generated by charge particles affect the motion of trailing particles in transverse and longitudinal plane. The amplitude of the wakefield is proportional to the electron beam intensity. Wakefields at high electron beam current result in the growth of electron beam instabilities in longitudinal and transverse plane [2,3]. These instabilities are called coupled bunch instabilities which degrade the accelerator performance.

The electron bunches circulating in the accelerator ring are influenced by these instabilities and start coherent oscillations. In general, the oscillations of electron beam damp out with natural damping processes. However, if the growth rate of the beam oscillation due to beam instabilities becomes higher than the damping rate then beam becomes unstable and every bunch starts oscillating with the betatron frequency in transverse plane and with synchrotron frequency in longitudinal plane. However, relative phase differences may exist between consecutive bunches, which are expressed by coupled bunch mode numbers. The phase difference $\Delta\phi$ between oscillations of consecutive bunches for n^{th} coupled bunch mode is given as [4]

$$\Delta\phi = \frac{2\pi n}{M} \qquad (1)$$

where,

M is the harmonic number of accelerator and
n is an integer that varies from 0 to $M-1$

Different coupled bunch modes can be observed as different frequency components in the spectrum of beam pickup signal [5]. Coupled bunch modes in transverse plane are referred to as transverse coupled bunch modes (TCBM) and the coupled bunch modes in longitudinal (along the direction of beam propagation) plane are referred to as longitudinal coupled bunch modes (LCBM).

Indus-2 is an electron synchrotron radiation source at Raja Ramanna Centre for Advanced Technology, Indore, which is operated at beam current up to 200 mA and beam energy 2.5 GeV [6]. For online measurement of the excitation levels of TCBMs, transverse coupled bunch instabilities measurement system is deployed in Indus-2.

With the help of this system, excitation of TCBM is observed in Indus-2 for beam current approximately above 150 mA. Saturation of beam current during beam injection, partial beam loss etc was observed during the beam operation at high current. These effects are attributed mainly to the excitation of transverse coupled bunch mode numbers 229 and 290. However, some other modes were also observed but the levels of excitation were not significant. For suppression of these instabilities, transverse multi-bunch feedback (TMBF) system (also referred as transverse bunch-by-bunch feedback system) is installed and commissioned in Indus-2. With the help of TMBF system, observed TCBMs are suppressed and 200 mA beam current at 2.5 GeV beam energy has been achieved. The TMBF system also helps in achieving good beam injection rate, bunch cleaning, betatron tune measurement etc. Scheme of transverse coupled bunch instabilities measurement system and TMBF system for Indus-2 are discussed in the following sections.

2. Measurement of transverse coupled bunch modes

For measurement and analysis of the transverse coupled bunch instabilities in Indus-2, an automated measurement system based on frequency domain analysis of beam position signal is developed and installed in the Indus control room.

For measurement of transverse coupled bunch instabilities, frequency components due to various excited modes are required to be identified in the spectrum of the beam position signal. As already stated, for M evenly filled equi-spaced bunches rotating in the accelerator ring, M coupled-bunch mode (CBM) numbers exist (n=0,1,…..,M-1). In the spectrum, the frequency component of the n^{th} transverse coupled bunch mode appears as

$$f_{n\_modt} = p\,f_{rf} \pm (n\,f_{rev} + f_{\beta}) \qquad (2)$$

where, p is an integer (0,1,2….), f_{rf} is the RF frequency, f_{rev} is revolution frequency and f_{β} is betatron frequency of accelerator. The longitudinal coupled bunch mode 'n' appears in the spectrum of beam intensity signal as

$$f_{n\_modl} = p\,f_{rf} \pm (\,n f_{rev} + f_{s}\,) \qquad (3)$$

where, f_s is synchrotron frequency. The transverse plane of the accelerator consists of horizontal *(X)* and vertical *(Z)* planes. For horizontal plane, frequency of n^{th} CBM is given as

$$f_{xn\_mod} = p\,f_{rf} \pm (\,n f_{rev} + f_{\beta x}\,) \qquad (4)$$

where, $f_{\beta x}$ is fractional betatron tune in horizontal plane. For vertical plane, frequency of n^{th} CBM can be given as

$$f_{zn\_mod} = p\,f_{rf} \pm (n\,f_{rev} + f_{\beta z}) \qquad (5)$$

where, $f_{\beta z}$ is fractional betatron tune for vertical plane[7]. For measurement of TCBM, frequencies which are given by equation (4) and equation (5) and their levels are measured in the spectrum of beam position signal.

2.1 *Hardware set-up*

The scheme of the transverse coupled bunch measurement system is shown in Figure T.1.1 [8].

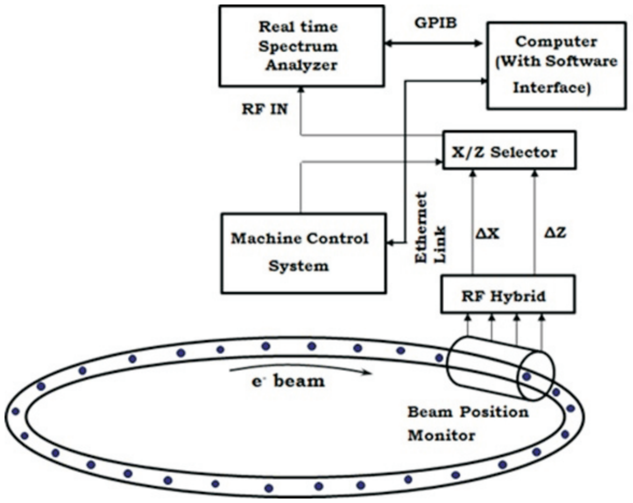


Fig. T.1.1: Scheme of transverse CBM measurement system of Indus-2 [8].

The measurement setup of TCBM consists of a beam position monitor (BPM), an RF hybrid unit, an RF switch, a real time spectrum analyzer (RTSA) connected with PC on GPIB interface.

BPM is used to generate the pick-up signals which are dependent on the position and intensity of electron beam passing through it. The output signals of BPM are fed to an RF hybrid unit, which generates the real time beam position signals ΔX and ΔZ respectively in horizontal and vertical plane. These position signals i.e, ΔX and ΔZ are fed sequentially using RF switch to RTSA for frequency domain analysis of beam position signals. RTSA is connected to a PC in the control room over GPIB interface.

2.2 *Application software*

System application software is developed in MATLAB for acquisition of beam spectrum from RTSA and subsequently its analysis for identification of the frequencies and allied levels of all TCBMs. The mode number, frequency of TCBM and amplitude of excited modes are displayed on Graphical User Interface (GUI) of the application. The RTSA is initialized with the predefined setting of center frequency, span, reference level, trace mode, no. of FFT points etc by the above mentioned application software. Beam current and beam energy information are acquired from the MATLAB server utility, already deployed in the machine control system. Data of the measured levels and frequencies of all TCBMs along with time stamp, beam current and beam energy are saved in an MS-Excel file. The data in the file can be used for analysis and study of the beam instabilities.

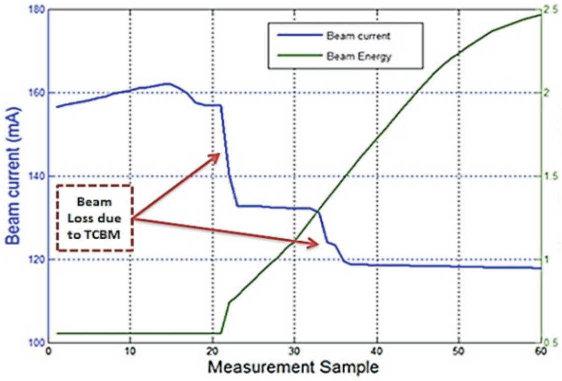


Fig. T.1.2: Typical graph showing the effect of transverse beam instability on the beam operation.

In Indus-2, the energy of stored beam at injection energy (~550 MeV) is increased to 2.5 GeV though the beam energy ramping process. During the beam energy ramping, many a time, beam loss has been observed due to the growth of instabilities. A typical event of partial beam loss during one of the beam energy ramping events is depicted graphically in Figure T.1.2. In this graph, partial beam loss is noticed at beam energy of ~560 MeV and 1.25 GeV to 1.5 GeV. The file having log of the TCBM data for later event i.e, the beam loss at 1.25 GeV to 1.5 GeV is analyzed. Figure T.1.3 is a plot of the TCBM data at 1.33 GeV for the same event. The plot clearly shows excitation of mode numbers 30 to 35 and mode numbers 250 to 260 with amplitudes about -50 dBm.

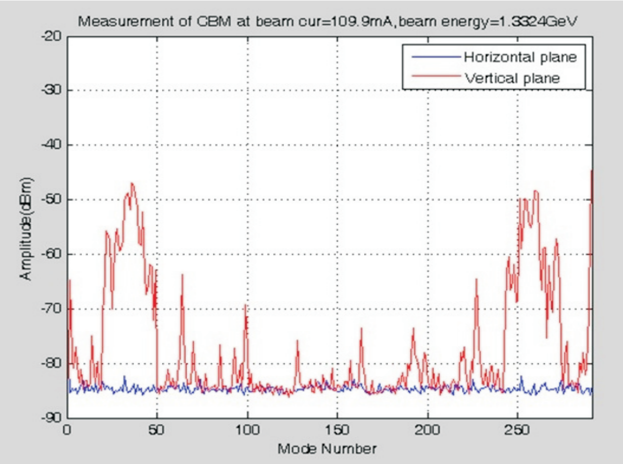


Fig. T.1.3: Typical graph of measured transverse CBM in Indus-2.

The coupled bunch instabilities can possibly be cured by

1. Avoiding the interaction of beam with higher order modes (HOM) of the RF cavities by its frequency tuning using plungers and optimizing the temperature of the cavities
2. Choosing suitable bunch filling pattern
3. Increasing the Landau damping by increasing tune spread
4. Proper designing of vacuum chambers with materials of low resistivity
5. Active feedback

If specific cures for instabilities listed above other than the “active feedback” are not adequate for reducing or eliminating coupled-bunch instabilities, active feedbacks are required. In Indus-2, in the present scenario, the interaction between the beam and the HOMs of RF cavities is minimized by optimum setting of plunger and temperature as far as transverse CBMs are concerned. For reducing the ion interaction with beam, appropriate bunch filling pattern is selected for Indus-2 beam operation. Towards the suppression of instabilities, field strength of sextupole magnets is optimized to increase the tune spread. Installation of the insertion devices with low gap vacuum chambers has increased the interaction of beam with the chambers. As frequent optimization of the vacuum structure is impractical, this has further aggravated the beam instability scenario. Therefore, TMBF system has been implemented in Indus-2 for the cure of transverse beam instabilities, which acts in horizontal as well as vertical plane.

3. Design and implementation of transverse multi-bunch feedback system

In the TMBF system, beam instabilities are detected using a BPM and an appropriate kick signal is applied on the electron beam through an electromagnetic actuator called stripline kicker to damp the beam oscillations.

The feedback system works in bunch-by-bunch mode i.e, in time domain processing mode. It exclusively steers each electron bunch by applying small kicks when the bunch passes through the kicker. As a consequence, the oscillations of each bunch get damped with damping time which depends on the amplitude of applied kick. The maximum strength of kick or correction signal required for suppression of beam instabilities is governed by the maximum growth rate of the instabilities, and it plays a pivotal role in the design of TMBF system.

3.1 RF power requirement for TMBF system

The growth rate of transverse beam instability has been assessed based on measured parameters of RF cavities namely shunt impedance, quality factor and frequencies of transverse dipole modes. The growth rate of the transverse

n^{th} coupled bunch mode instability at frequency f_{x/zn_mod} excited by any resonant structure in the vacuum envelope is given by the relation

$$\frac{1}{\tau} = \frac{\beta_{\perp} I_b f_{rev}}{2\left(E_b/e\right)} R_{\perp}\left(f_{X/Zn\_\mathrm{mod}}\right) \qquad (6)$$

Where, I_b is beam current, E_b is beam energy, $\beta_{\perp}$ is the lattice beta function at the location of resonant structure, $R_{\perp}(f_{x/zn\_mod})$ is transverse impedance of resonant structure for frequency f_{x/zn_mod} [9]. The maximum growth of the beam instability may occur when the frequency of any coupled bunch mode resonates with the HOM frequency of RF cavities. For Indus-2, calculated value of maximum growth rate is approximately 10^5 per second.

The RF power required to be applied to stripline kicker to damp the CBM instability having growth rate ($1/\tau$) is given by [10]

$$P = \frac{2}{R_{sh}\,\beta_{kick}}\left(\frac{E_b}{e}\right)^2\left(\frac{T_0}{\tau}\right)^2\left(\frac{A}{\sqrt{\beta_{pick}}}\right)^2 \qquad (7)$$

where,

R_{sh} is transverse shunt impedance of the kicker

β_{kick} is beta function at the kicker location

T_0 is revolution time of the bunch

A is initial amplitude of the bunch oscillation

β_{pick} is beta function at the pick-up/BPM location

e is the charge on electron

With the help of equation (6) and equation (7) the RF amplifier requirement has been calculated, and two 100 watt RF amplifiers have been installed for amplification of the kick signal for each transverse plane.

3.2 System description

As already stated there are number of ways to combat beam instabilities and that the active feedback is the most effective of all. Active feedback system for transverse plane installed in Indus-2 is referred to as the transverse multi-bunch feedback (TMBF) system or transverse bunch-by-bunch feedback system. Scheme of the TMBF system for Indus-2 is shown in Figure T.1.4.

The feedback system is an active mechanism to damp transverse instabilities by sensing the oscillation generated in a bunch due to instabilities ,and applying an RF kick to the same bunch ahead. One of the beam position monitors (BPM) of Indus-2 has been used to pick up the beam oscillation signals. Outputs of the BPM are fed to an RF hybrid detector to produce the real time horizontal (ΔX) ,vertical (ΔZ) and longitudinal (Σ) signals proportional to the horizontal, vertical and longitudinal oscillations respectively at the BPM location. The outputs of the RF hybrid detector are fed to RF front/back end unit [11]. Outputs of the RF front/back end unit are the base band signals of oscillations with programmable gain and phase control. The outputs of this unit are fed to the respective digital feedback processing unit [12].

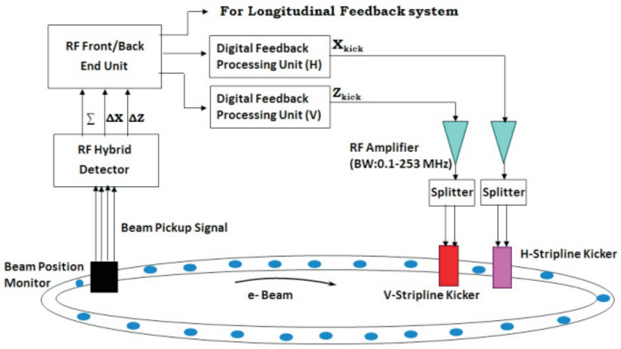


Fig. T.1.4: Scheme of transverse multi-bunch feedback system.

Based on the frequency and amplitude of oscillations of individual bunch, correction signals are generated by the processing units. The correction signals (X_{kick},Z_{kick}) are adjusted in phase and amplitude. These kick signals are amplified using broadband RF amplifiers and split into two out of phase signals (with 0° and 180° phase) using high power splitter. These out of phase signals are fed to the stripline kickers for applying the correction [13].

3.3 Application software

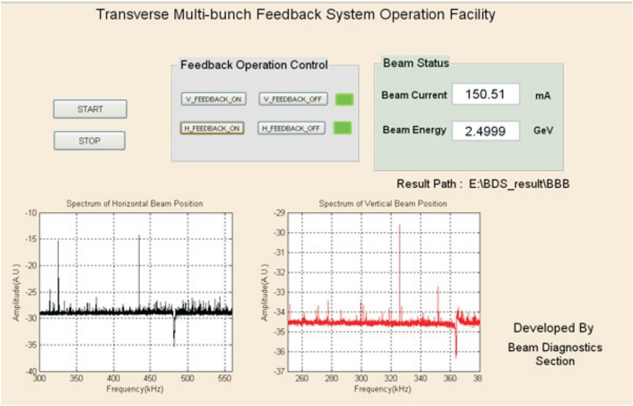
Application software of the transverse multi-bunch feedback system is developed in MATLAB. Main components of the application software are the local MATLAB server, MATLAB client or graphical user interface (GUI), and the communication modules developed for communication between the local MATLAB server and digital feedback processing units and also for communication with database server in main control system. A snapshot of the GUI panel is shown in Figure T.1.5. For adjustment of phase and amplitude, the software interacts with the RF front/back end and also with digital feedback processing units.

Application software acquires the bunch by bunch data and also applies signal processing techniques to improve the signal to noise ratio of the acquired data. The features of the software are as follows,

- It has a user interface with single button control of feedback system operation.
- It allows operation of the feedback system during all the modes of beam operation namely beam injection, beam

energy ramping and stored beam. It uses software-based phase tracking between reference RF signal and bunch pickup signal and also performs the gain control depending on the beam current and beam energy.

- It has provision for independent control of horizontal and vertical feedback systems.
- Software also logs the feedback status and values of the feedback parameters with beam current and beam energy.


Transverse Multi-bunch Feedback System Operation Facility

Beam Status

Beam Current 150.51 mA

Beam Energy 2.4999 GeV

Result Path : E:\BDS_result\BBB

Developed By
Beam Diagnostics
Section

Fig. T.1.5: Snapshot of the GUI of transverse multi-bunch feedback system.

4. Commissioning of TMBF system

After installation of the TMBF system in Indus-2, various beam experiments were carried out during commissioning of feedback system. Observations and results obtained with the feedback system are given below.

4.1 Growth and damping time measurement

Initially, experiment with single bunch beam operation was carried out. The feedback loop of the process was closed by adjusting the timing, filter coefficients and RF power. Growth and damping time of instabilities were measured. Typical measurement of growth and damping time of transverse beam instability for single bunch is shown in Figure T.1.6.

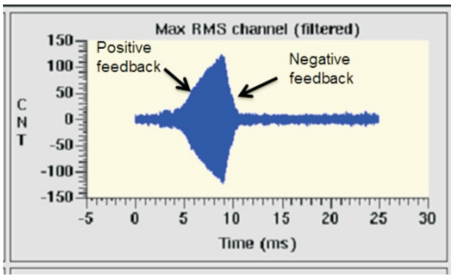


Fig. T.1.6: Typical graph showing growth and damping of transverse beam instability of single bunch at 2 mA, 550 MeV.

Coupled bunch instability (mode no. 290) was observed when the beam current was at 20 mA and the beam energy was 550 MeV with all bunches filled. Instability was suppressed completely using feedback system. Figure T.1.7 shows the measurement result. For this, the feedback system was kept off for measuring the growth of instability and the feedback system was turned on after 12 ms to damp the instabilities in the beam.

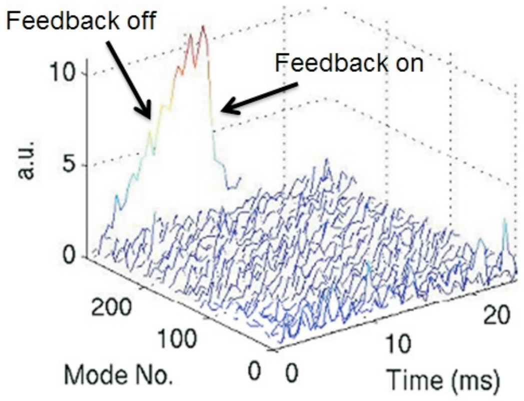


Fig. T.1.7: Typical graph showing growth and damping of transverse CBM no. 290 with all bunches filled.

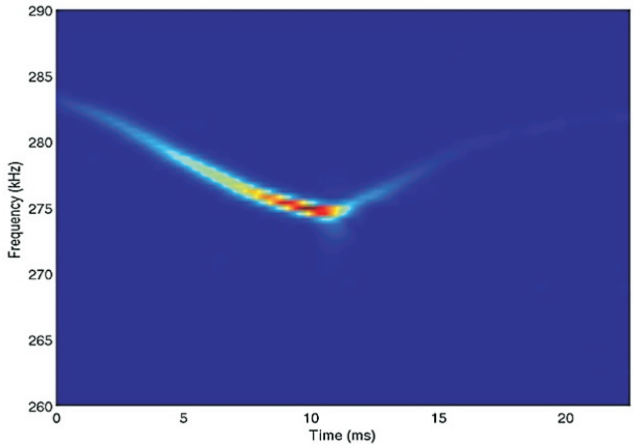
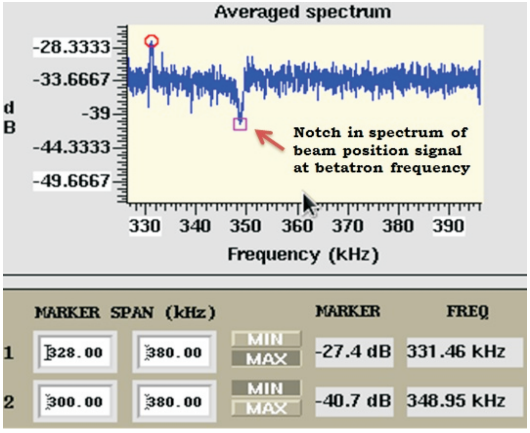


Fig. T.1.8: Typical graph of change in vertical betatron frequency during growth and damping of beam instability in vertical plane.

When the feedback system was off, increase in the amplitude of oscillations was observed with a significant negative shift in the vertical betatron tune. Figure T.1.8 shows change in vertical betatron frequency during growth of oscillations (CBM no. 290) and damping of beam instability when the feedback system was switched on.

4.2 Beam operation with TMBF system

Transverse coupled bunch instabilities are suppressed by the feedback system. In this condition, spectrum of the beam position signal shows a notch at betatron frequency. Figure T.1.9 shows that the measurement of frequency of notch provides value of the betatron tune and can be used for online measurement of the tune value.



	MARKER SPAN (kHz)		MARKER	FREQ
1	328.00	380.00	-27.4 dB	331.46 kHz
2	300.00	380.00	-40.7 dB	348.95 kHz

Fig. T.1.9: Typical spectrum of beam position signal with TMBF ON.

In routine beam operation, functionality of TMBF system and improvement in the machine performance due to feedback system is constantly monitored.

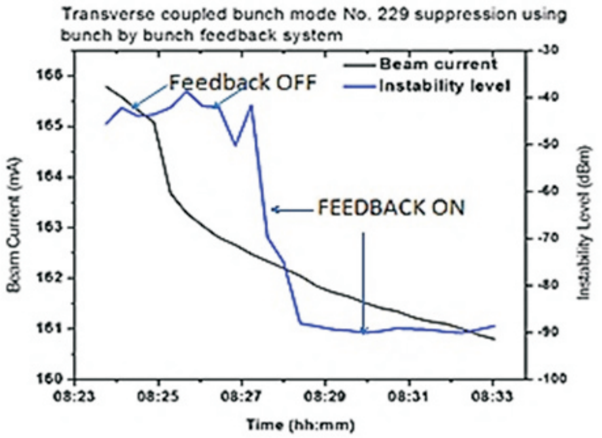


Fig. T.1.10: Beam instability suppression with TMBF system.

TMBF system has played an important role in achieving beam current of 200 mA at 2.5 GeV beam energy. During the initial trials to achieve stable high beam current operation, it was observed that level of horizontal instability of coupled bunch mode (Mode No. 229) was significantly high. With the help of feedback system, the level of the instability was suppressed as shown in Figure T.1.10.

Typical beam operation of Indus-2 with 200 mA beam current and 2.5 GeV beam energy is shown in Fig T.1.11.The effect of feedback system on vertical beam size has been observed using x-ray diagnostic beamline (BL-24) of Indus-2. It is observed that the vertical beam size is reduced from 105 microns to 71 microns by the application of feedback.

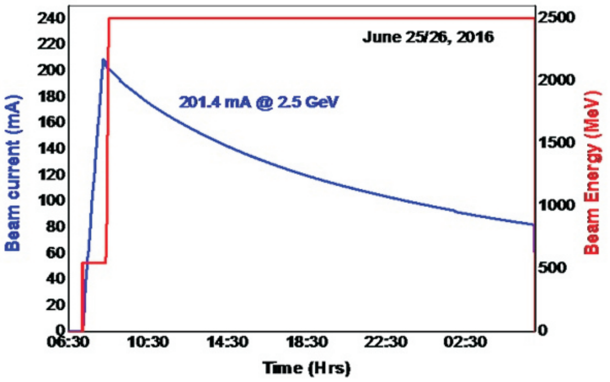


Fig. T.1.11: Typical graphs of beam current operation in Indus-2 with beam current ~200 mA @ 2.5 GeV.

4.3 Improvement in beam injection

With feedback system, improvement in the injection rate was also observed. This is due to the reduction in damping time of the beam oscillations in vertical plane during beam injection. Transients in the injected beam have also been observed when injection kickers are triggered. Beam oscillation in vertical plane with long damping time was observed during beam injection. It can be seen from Figure T.1.12 that with feedback on, the beam oscillation in vertical plane gets damped rapidly and the damping time is reduced to ¼th of that without feedback.

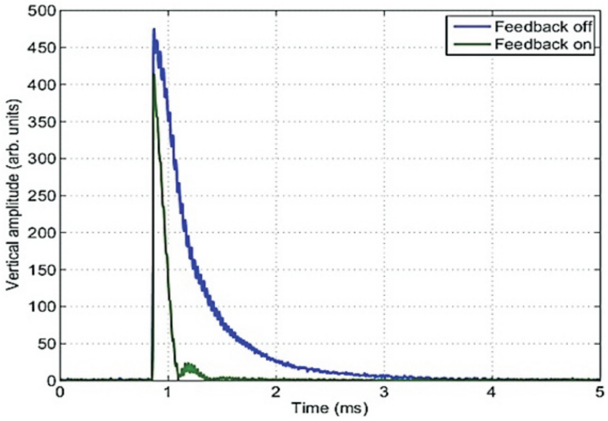


Fig. T.1.12: Typical graph showing damping of vertical beam oscillation with and without feedback system on.

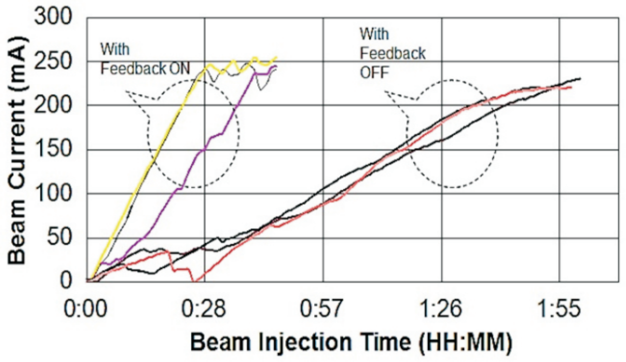


Fig. T.1.13: Typical graphs of beam current injections in Indus-2 with and without feedback system on.

The feedback system helps to reduce the beam injection time by a factor of about 1.3-1.5 times. Typical graphs of beam current injection in Indus-2 with and without feedback system on are shown in Fig T.1.13.

4.4 Bunch cleaning facility

Information of the bunch filling pattern is also provided by this system. Typical bunch filling pattern detected by TMBF system is shown in Figure T.1.14.

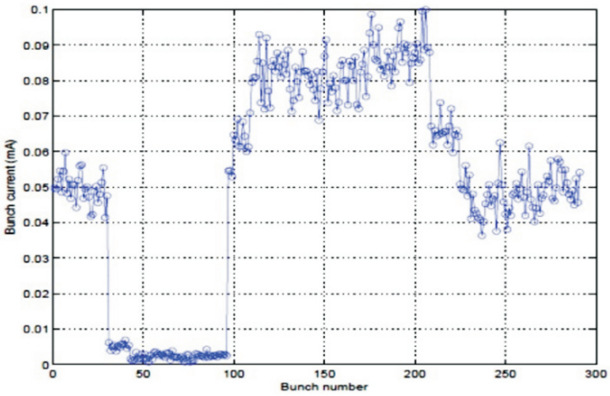


Fig. T.1.14: Typical graph for measured bunch filling pattern of Indus-2 using bunch current data acquisition facility of TMBF system.

An important feature of the TMBF system is cleaning of selected bunches from the filled bunch pattern. Figure T.1.15 shows bunch pattern after cleaning of every 3rd bunch from the filled pattern shown in Figure T.1.14.

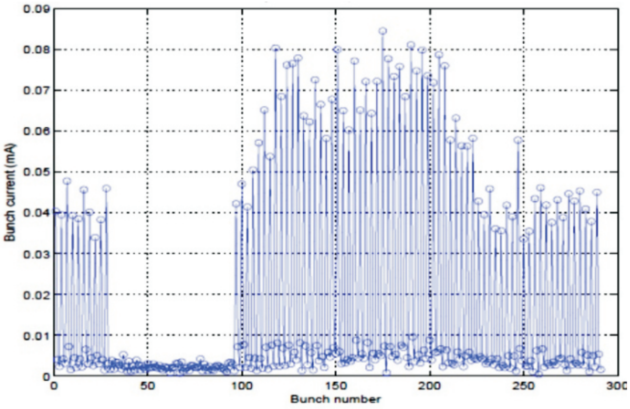


Fig. T.1.15: Measured bunch filling pattern of Indus-2 after bunch cleaning.

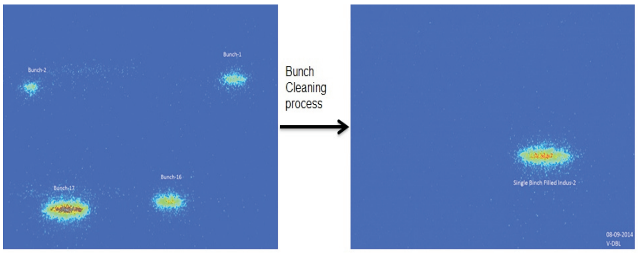


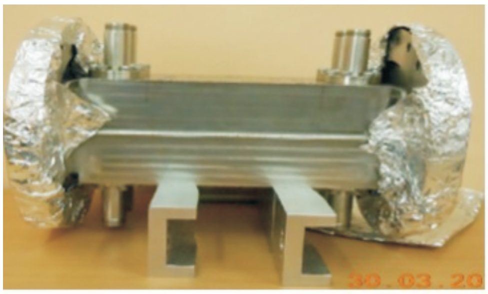
Fig. T.1.16: Streak camera images of typical multi-bunch and single-bunch beam obtained after bunch cleaning.

Single bunch operation is achieved in Indus-2 only by using the bunch cleaning feature of the feedback system. Images captured by streak camera at visible diagnostic beamline (BL-23) of Indus-2 is shown in Figure T.1.16. This shows the typical bunch cleaning operation to get the single-bunch beam from a multi-bunch beam.

4.5 Optimization and upgrades of TMBF system

In Indus-2, horizontal and vertical betatron tunes change during the beam energy ramping process. Thus optimization of digital filters of feedback system has been carried out to achieve stable performance of the feedback system for wide beam spectrum in vertical and horizontal planes. It was also observed that the horizontal position signal (ΔX) used in the horizontal feedback system had significant longitudinal oscillation components. To remove this longitudinal oscillation signal, number of taps for feedback filter was optimized. The centre frequency of the feedback filters has been also optimized to minimize coupling between horizontal and vertical plane.

With the installation of insertion devices in long straight sections in Indus-2, the vertical aperture of the vacuum envelope has reduced which has increased the interactions between beam and the vacuum structure. In order to enhance the capabilities of feedback system to suppress increased level of instabilities, two new stripline kickers shown in Figure T.1.17 with higher transverse shunt impedance (≥20 kΩ for vertical plane and ≥ 10 kΩ for horizontal plane respectively), minimum power reflection (better than -20 dB up-to 250 MHz bandwidth) at feeding ports have been developed and installed in Indus-2. These have enhanced the gain of feedback system for controlling beam instability with higher growth rate.



(a)

(b)

Fig. T.1.17:Snapshot of new stripline kicker assemblies for TMBF system of (a) horizontal plane and (b) vertical plane.

5. Conclusion

TMBF system has been successfully implemented in Indus-2. The beam operation of Indus-2 has significantly improved after the implementation of the feedback system. Application software developed for operation of feedback system is easy to use and requires bare minimum operator interaction. It has data logging facility which has been used many times to investigate the beam operation related issues and phenomena. The system also provides other facilities like bunch-by-bunch betatron tune information, bunch cleaning facility, bunch filling pattern measurement etc. With the installation of new stripline kickers, RF power requirement during regular operation has reduced significantly.

6. Acknowledgement

The authors would like to thank the colleagues of Beam Diagnostics Section for their contribution in the design, development and commissioning of TMBF system. Authors also thank the members of working group for their involvement in the planning and execution of various activities related to TMBF system. Help and support received from Indus operation crew members in the implementation of the feedback system is also thankfully acknowledged.

References

[1] J.W Flanagan *et al.*, “Overview of beam instrumentation for high-intensity storage rings”, Asian Particle Accelerator Conference, APAC-2001,China.

[2] A.W. Chao, “Physics of Collective Beam Instabilities in High Energy Accelerators”, New York: Wiley, 371 p, 1993.

[3] Wenzhong Wu, “Feedback Systems for Control of Coupled-bunch Instabilities in the Duke Storage Ring”, Ph.D Dissertation, Department of Physics, Duke University, 2012.

[4] F. J. Sacherer, “Transverse bunched beam instabilities–theory”, 9th International Conference on High Energy Accelerators, Stanford, California, USA, pp. 347–351, 1974.

[5] Jeff Homes *et al*., “Review of collective effects” United States Particle Accelerator School (USPAS), January 2009 ,Vanderbilt.

[6] http://www.rrcat.gov.in/technology/accel/indus2.html

[7] J. M. Byrd and J. N. Corlett, "Study of coupled-bunch collective effects in the ALS," Proceedings of International Conference on Particle Accelerators, Washington, DC, USA, 1993, pp. 3318-3320, vol.5.doi: 10.1109/PAC.1993.309638.

[8] S. Yadav, T. A. Puntambekar, P. V. Varde, “Development of Front-end Software for Beam Parameters Measurement for Indus-2 Electron Synchrotron”, International Journal of Computer Applications (IJCA), USA,ISSN No. 0975 – 8887.

[9] A. Fabris,“Coupled bunch instability calculations for the ANKA storage ring”, Particle Accelerator Conference, New York City, 1999.

[10] U Iriso *et al*., “Design of the stripline and kickers for ALBA”, 9th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, DIPAC09, pp. 86-89.

[11] https://www.dimtel.com/products/fbe_lt

[12] https://www.dimtel.com/products/igp12

[13] Surendra Yadav *et al*., “Operational experience of transverse bunch by bunch feedback system of Indus-2”, Indian Particle Accelerator Conference, InPAC-2018,Indore, 2018.